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Sustainable Charcoal Briquettes from Canarium indicum Shell Waste Using Red Dragon Fruit Peel as a natural Binder

Irwan Said[1*], Sitti Rahmawati[1], Purnama Ningsih[1], Afadil[1], Fadila[1]

[1] Departement of Mathematics and Natural Sciences Education, Faculty of Teacher Training and Education, Tadulako University, Indonesia

* Corresponding author: irwansaid758@gmail.com

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Abstract: Walnut shell waste is an agricultural lignocellulosic residue containing approximately 17.74% cellulose, 36.06% hemicellulose, and 36.90% lignin, which makes it a promising feedstock for solid biofuel production. Red dragon fruit peel, which contains about 14.6–20.14% pectin, can act as a natural binder for biomass briquettes. This study investigates the use of walnut shell waste and red dragon fruit peel adhesive for the production of charcoal briquettes as an alternative renewable fuel. Charcoal briquettes were produced from walnut shell waste using red dragon fruit peel adhesive at three concentrations (15 g, 20 g, and 25 g per 100 g of charcoal). An experimental laboratory approach was employed to evaluate the physical and chemical properties of the briquettes. Key parameters measured included density, calorific value, compressive strength, moisture content, ash content, volatile matter, and fixed carbon. The results were compared with the Indonesian National Standard (SNI) for charcoal briquettes. The briquettes produced with 15 g of red dragon fruit peel adhesive per 100 g of charcoal exhibited the most favourable performance, with a density of 0.7808 g/cm³, a calorific value of 4716.28 cal/g (≈19.7 MJ/kg), a compressive strength of 14.99 kg/cm² (≈1.47 MPa), a moisture content of 5.98%, an ash content of 7.64%, a volatile matter content of 10.89%, and a fixed carbon content of 81.09%. Most parameters met the SNI requirements, while the calorific value and compressive strength were slightly below the recommended thresholds. These findings indicate that walnut shell waste combined with red dragon fruit peel adhesive can yield charcoal briquettes with generally good physical and

chemical properties, highlighting the potential of this biomass binder system as a source of renewable solid fuel. Further optimisation of binder formulation and processing conditions is warranted to fully meet standard performance criteria and to support wider practical application.

Keywords: walnut shell; red dragon fruit peel adhesive; pectin binder; charcoal briquettes; biomass; renewable energy.

以红心火龙果果皮为天然粘结剂制备的 *Canarium indicum* 果壳废弃物可持续木炭压块

摘要：胡桃壳废弃物是 种典型的农业木质纤维素残余物，其纤维素、半纤维素和木质素含量分别约为17.74%、36.06%和36.90%，因此具有作为固体生物燃料原料的良好潜力。红心火龙果果皮中果胶含量约为14.6%–20.14%，可作为生物质型煤的天然粘结剂。本研究以胡桃壳废弃物为原料、以红心火龙果果皮粘结剂为结合剂，制备生物质型木炭压块，以期开发一种可替代的可再生燃料。实验采用实验室控制条件下的对比试验方法，分别在胡桃壳木炭100 g中加入15 g、20 g和25 g红心火龙果果皮粘结剂制备压块，并对所得压块的物理和化学性质进行测试与评价。主要测试指标包括密度、发热量、抗压强度、含水率、灰分、挥发分和固定碳含量，并与印度尼西亚国家木炭压块标准（SNI）进行对比分析。结果表明，当粘结剂用量为15 g/100 g木炭时，各项性能表现最佳：压块密度为0.7808 g/cm³，发热量为4716.28 cal/g（约19.7 MJ/kg），抗压强度为14.99 kg/cm²（约1.47 MPa），含水率为5.98%，灰分为7.64%，挥发分为10.89%，固定碳含量为81.09%。除发热量和抗压强度略低于SNI推荐限值外，其余大部分指标均满足相关标准要求。研究结果表明，胡桃壳废弃物与红心火龙果果皮粘结剂的组合能够制备出物理与化学性质总体较优的木炭压块，显示出该生物质–粘结剂体系作为可再生固体燃料原料的应用潜力。未来仍需通过进一步优化粘结剂配方和工艺参数，以全面满足标准性能要求并推动其在实际能源利用中的推广应用。

关键词：胡桃壳；红心火龙果果皮粘结剂；果胶粘结剂；木炭压块；生物质；可再生能源

1. Introduction

Fossil fuels are the most important source of energy for humans to date, particularly petroleum, coal, and natural gas, which have been around for thousands of years. With the growing population and technological advances, the demand for fossil fuels will continue to increase. However, this is not in line with the dwindling availability of fossil energy, as fossil energy is a non-renewable energy source. As a result, energy sources may become scarce or even depleted in the future [1].

Indonesia also faces similar challenges in the energy sector. The main issue is the mismatch between increasing energy consumption and the required energy supply. Energy use in Indonesia is increasing by 3.46% annually. The largest energy consumption is in the industrial sector at 37.17%, followed by the household sector at 29.43%, transportation at 28.10%, commercial at 3.24%, and others at 2.04%. One alternative is the use of biomass energy [2].

Biomass energy is a source of energy derived from renewable natural resources, making it a potential alternative to renewable energy sources. Biomass used as an alternative fuel must be environmentally friendly, easily obtainable, economical, and widely used by the general public [3].

Briquettes are an alternative biomass fuel to fossil energy derived from agricultural waste, such as plant parts. The raw materials for making these briquettes can be parts that are intentionally used as the main ingredient or residues or waste from agro-industrial production or processing [4].

The cashew plant is a plant native to Indonesia that has the potential to be developed as a food and medicinal product. However, the skin and shell of cashew nuts are the main source of lignocellulose that can be used to produce renewable energy fuel by utilizing biomass. The nutshell is a lignocellulosic agricultural waste consisting of cellulose (17.74%), hemicellulose (36.06%), and

lignin (36.90%). By leveraging this potential, opportunities can be created to produce environmentally friendly renewable energy [5].

The briquette production process is important for adding a binder to enhance the physical properties of the briquettes. One waste material that can be utilized as a binder is red dragon fruit peel. Red dragon fruit peel contains pectin with a relatively high content, approximately 10.80% [6] while dried red dragon fruit has a pectin content of approximately 14.6–20.14% [7]. Pectin is a hydrocolloid compound that can be utilized in gel production [8]. Therefore, the pectin contained in dragon fruit peel can be used as a binder in charcoal briquette production.

Another criterion that plants must meet as an energy source is their cellulose and lignin content [9]. All materials containing lignin and cellulose can be densified or compacted [10]. The main raw material for charcoal briquette production is lignocellulose. Lignocellulose comprises of cellulose, hemicellulose, and lignin [11].

Charcoal briquette production has been widely carried out using various materials and different variations. Among them, [12] conducted research to create walnut shell briquettes that have economic value and can replace or be equivalent to coal briquettes. The production process of walnut shell samples involves carbonization using mesh sizes 28, 65, and 80. The research results indicate that walnut shell briquettes can compete with coal briquettes in terms of particle size, calorific value, volatile matter content, and other properties.

The selection of walnut shell waste (*Canarium indicum L.*) and red dragon fruit peel as research objects is based on several key criteria. Walnut shells have a high lignocellulose composition cellulose, hemicellulose, and lignin that enables efficient combustion and high calorific value, making them ideal as biomass feedstock [6]. Meanwhile, red dragon fruit peel is abundant agricultural waste with a significant pectin content, functioning effectively as a natural binder that improves briquette cohesion and reduces the use of synthetic adhesives. The combination of these two materials aligns with the principles of circular economy and waste valorization, as it transforms organic waste into value-added renewable energy products.

Practically, Practically, the findings of this study are expected to provide a sustainable alternative energy source that can be applied at both household and industrial levels, reducing waste accumulation and dependency on fossil fuels. Theoretically, the research contributes to the development of knowledge in biomass energy conversion, particularly the interaction between lignocellulosic structure and natural binder properties in determining the physical and thermal characteristics of briquettes [11].

Based on the above background, research on charcoal briquettes typically uses sago or tapioca flour as a binder, with no studies using dragon fruit peel extract. Therefore, the researcher aims to conduct a study on the "characteristics of charcoal briquettes from walnut shell waste (*Canarium Indicum L.*) using red dragon fruit peel as a binder."

2. Method

2.1. Charcoal Production

Walnut shells are dried under the sun for 3 days until they are completely dry. The walnut shells are then placed in an empty can and burned until they turn into charcoal, as indicated by the absence of smoke. Once cooled, the charcoal is ground into a fine powder using a mortar and pestle, then sieved using a 120-mesh sieve. The charcoal powder is then placed in a sealed container before mixing with an adhesive.

To ensure reproducibility, the carbonization process was performed under semi-controlled pyrolysis conditions, maintaining limited oxygen access by using a metal container with small air vents. The burning process was carried out for approximately 45–60 minutes until all the shells were carbonized uniformly. The resulting charcoal was allowed to cool naturally at room temperature (25–27°C) before being ground. All grinding and sieving steps were performed using sterilized equipment to prevent contamination, and each batch of charcoal was labeled according to production date and temperature conditions.

2.2 Charcoal Briquette Production

Charcoal powder from walnut shells is placed in a container, then red dragon fruit peel adhesive powder is added at concentrations of 15g, 20g, and 25g, along with 85 ml of distilled water. Then mix the charcoal powder and adhesive flour evenly. After mixing, the charcoal briquettes are molded in a briquette mold and dried under sunlight until dry.

All mixtures were prepared at a constant ambient temperature of 28 ± 2°C and relative humidity of 70–80%. The adhesive was prepared by drying red dragon fruit peels at 60°C for 24 hours, then grinding them into fine powder and sieving with a 100-mesh sieve. The briquette mixture was stirred manually for 10 minutes until it was homogeneous and formed a plastic-like texture. The molding process used cylindrical molds (diameter 3 cm, height 2 cm) under a constant manual pressure of approximately 5 kg/cm² to ensure uniform density. Drying was conducted under direct sunlight for 2 days (8 hours/day) until the weight remained constant, indicating stable moisture content. Three replications were carried out for each concentration level to enhance data reliability.

2.3 Charcoal Briquette Testing

The parameters tested for charcoal briquettes in this

study were density, compressive strength, calorific value, moisture content, ash content, volatile matter content, and fixed carbon content. Each test was conducted in triplicate, and the mean values were reported to minimize measurement error. Standard testing protocols were based on SNI (Indonesian National Standard) references, and all instruments were calibrated before measurement.

2.4 Density

The principle for determining density or specific gravity is expressed in the ratio between the weight and volume of charcoal briquettes [13].

$$\textbf{density} = \frac{\text{sample mass (g)}}{\text{sample volume cm}^3} \quad (1)$$

Each briquette was weighed using an analytical balance with 0.001 g precision, and its volume was measured using the displacement method in a graduated cylinder containing distilled water to reduce measurement bias.

2.5 Strong Pressure

Compressive strength testing was performed using a Universal Testing Machine (UTM).

$$\textbf{Kt } (\textbf{kg/cm}^2) = \frac{\textbf{F (N)}}{\textbf{A(cm}^2\textbf{)}} \quad (2)$$

The test was performed by applying a uniform load until the briquette fractured. The applied force (F) was recorded, and the surface area (A) was calculated from the briquette's dimensions. Each sample was tested three times, and the average value was used for analysis. The testing temperature was controlled at 25°C to avoid the effect of humidity on structural integrity.

2.6 Determination of Water Content

Water content is basically the evaporation of free water contained in briquettes until the water content reaches equilibrium with the surrounding air. The formula for calculating water content according to SNI 06-3730-1995 (section 5.2) is as follows:

$$\textbf{moisture content } (\%) = \frac{\textbf{w}_1}{\textbf{w}_2}\textbf{x 100 } \% \quad (4)$$

Samples were weighed before and after being dried in an oven at 105°C for 2 hours. The procedure was repeated until a constant weight was achieved to ensure complete evaporation of free water [14].

2.7 Determination of Ash Content

The ash content in charcoal briquettes comprises minerals that cannot be eliminated or vaporized during combustion. The ash content is determined according to SNI 06-3730-1995 (section 5.3) as follows:

$$\textbf{ash content } (\%) = \frac{\textbf{w}_1}{\textbf{w}_2}\textbf{x 100 } \% \quad (5)$$

Samples were combusted in a muffle furnace at 750°C for 3 hours until a constant gray-white residue formed. The crucibles were cooled in a desiccator before weighing to avoid moisture absorption [15].

2.8 Determination of Volatile Substance Content

The volatile matter content is determined by evaporating all volatile substances in charcoal briquette powder, excluding water. The volatile matter content is quantified as a percentage according to SNI 01-6235-2000 (section 6.3) as follows:

$$\textbf{ash content } (\%) = \frac{\textbf{w}_1-\textbf{w}_2}{\textbf{w}_1}\textbf{x 100 } \% \quad (6)$$

Approximately 1 g of each sample was heated in a closed crucible at 950°C for 7 minutes in a muffle furnace. After cooling in a desiccator, the remaining mass was recorded, and calculations were performed to determine volatile matter content [13].

2.9 Determination of Bound Carbon Content

Bound carbon refers to the portion of carbon (C) in briquettes, excluding water, volatile matter, and ash components. The bound carbon concentration is delineated in SNI 06-3730-1995 (section 5.6) as follows:

Bound carbon content (%) = (100%) – (ash content + Volatile matter content) % (7)

This value was calculated indirectly from previously obtained data. The analysis provides insight into the energy potential and combustion stability of the briquettes. Higher bound carbon content indicates better fuel performance and longer burning duration

3. Result

3.1 Charcoal Briquette Production

Each briquette molding treatment produced 9 charcoal briquettes, with each treatment having a concentration variation of 15g, 20g, and 25g. The charcoal briquettes produced were cylindrical in shape with a height of 2 cm and a diameter of 2.7 cm. The results obtained from this study can be seen in Table 1.

Table 1. Data Analysis of Charcoal Briquette Characterization from Walnut Shells

Charcoal Mass (grams)	Adhesive Weight Variations			Indonesia National Standard (SNI)
100 grams	15 gram	20 gram	25 gram	-
Density (g/cm^3)	0.7805	0.8079	0.8508	> 0,5–0,6
Compressive Strength (kg/cm^2)	14.9884	12.3119	5.8892	> 50
Calorific Value	4716.28	3794.37	3734.75	5000
(cal/g)	5.9777	6.7283	7.3874	< 8
Moisture Content (%)	7.64	10.86	10,96	< 8

Ash Content (%)	10.89	9.96	9.01	< 15
Volatile Matter Content (%)	81.47	79.18	80.03	77

3.2. Testing the Characteristics of Charcoal Briquettes

3.2.1 Density

Density is the result of comparing the mass and volume of charcoal briquettes [14]. For achieve good density values, the researchers produced charcoal briquettes from walnut shells using a 120-mesh sieve to obtain finer powder. The density values in this study are shown in Figure 1.

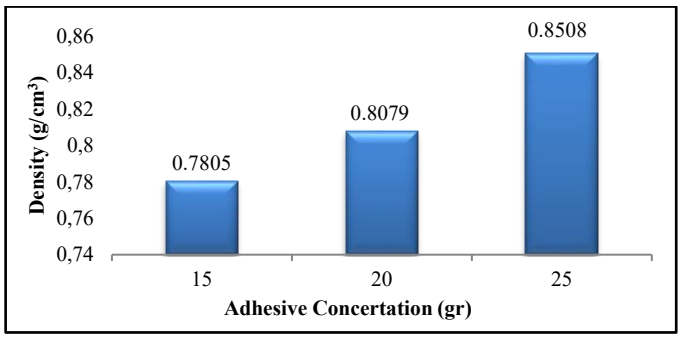

Figure 1. Bar chart showing the concentration of density of charcoal briquettes made from walnut shells

3.2.2. Strong Pressure

Compression testing is a mechanical testing tool used to measure and determine the strength of an object against compressive forces. A greater compressive strength number indicates superior resistance to external pressure and a reduced likelihood of charcoal briquettes crumbling [15].

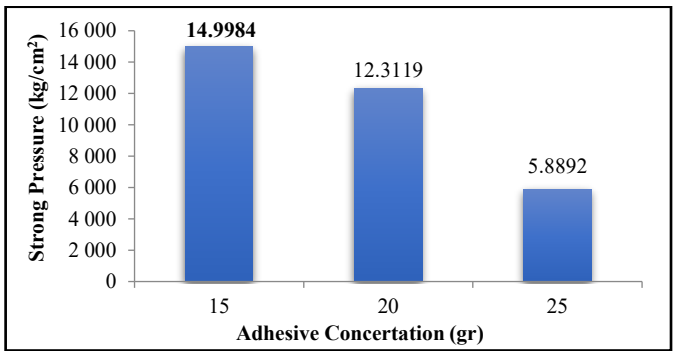

Figure 2. Bar chart showing the concentration of strong adhesive pressure briquettes made from walnut shells

3.2.3Calorific Value

Based on Figure 4, the research results show that the highest calorific value of walnut shell charcoal briquettes was found at a binder concentration of 15 grams, which was 4716.28 cal/g, and the lowest calorific value was found at a binder concentration of 25 grams, which was 3734.75 cal/g.

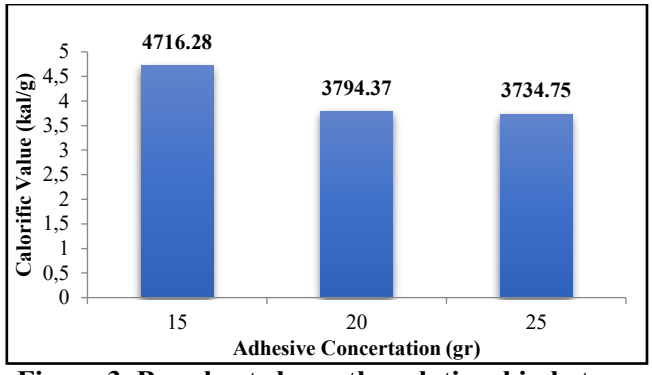

Figure 3. Bar chart shows the relationship between adhesive concentration and the calorific value of charcoal briquettes made from walnut shells

3.2.4 Water Content

The research results indicate that as the binder concentration increases, the moisture content also increases. This is because adding red dragon fruit peel binder concentration can increase the moisture content. Based on the findings of the study conducted on three adhesive concentrations, the average values obtained were as follows: adhesive concentration of 15 grams with a moisture content of 5.9777%, adhesive concentration of 20 grams with a moisture content of 6.7283%, and adhesive concentration of 25 grams with a moisture content of 7.3874%.

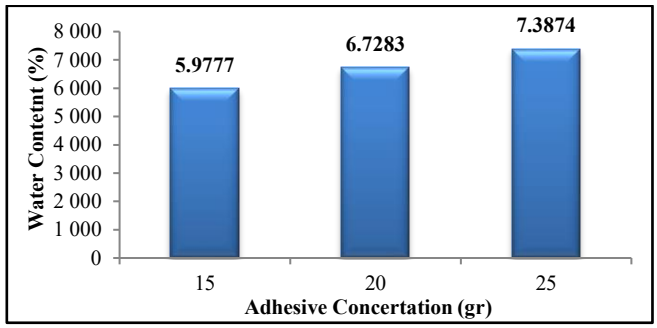

Figure 4. Bar chart showing the relationship between adhesive concentration and moisture content of coconut shell charcoal briquettes

3.2.5 Ash Content

According to the test outcomes in Figure 6, it was found that the ash content of walnut shell charcoal briquettes rose with higher adhesive concentrations. The adhesive concentration of 15 grams was 8.02%, the adhesive concentration of 20 grams was 10.86%, and the adhesive concentration of 25 grams was 10.96%.

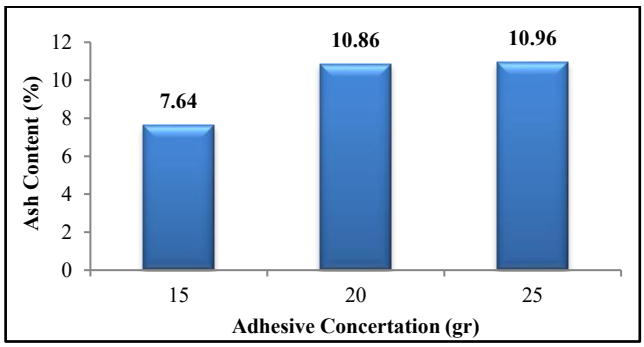

Figure 5. Bar chart showing the relationship between adhesive concentration and ash content of coconut shell charcoal briquettes

3.2.6 Volatile Substance Content

In Figure 6, the highest concentration of volatile compounds was found in the 15-gram adhesive concentration, which was 10.89%, followed by the 20-gram adhesive concentration and the lowest concentration of 25 grams, which was 9.01%.

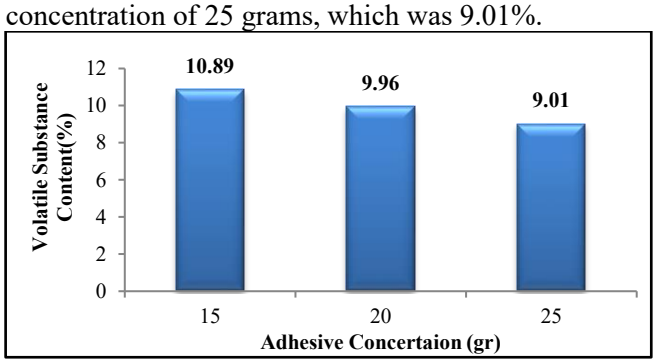

Figure 6. Bar chart shows the relationship between adhesive concentration and the concentration of volatile compounds in walnut shell charcoal

3.2.7 Bound Carbon Content

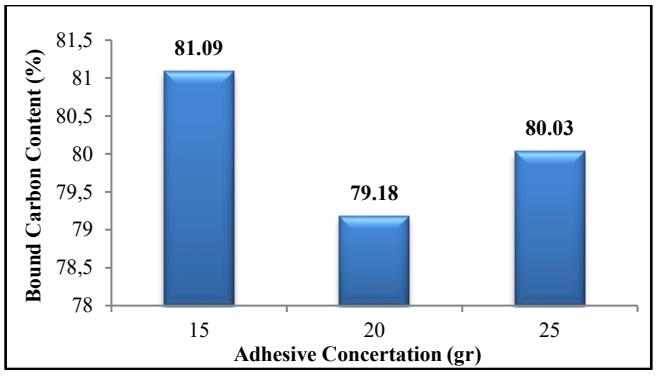

Figure 7. Bar chart showing the relationship between adhesive concentration and carbon content in charcoal briquettes made from walnut shells

Figure 7, charcoal briquettes made from walnut shells at a binder concentration of 20 grams experienced a decrease followed by an increase at a concentration of 25 grams.

3.2.8 Analysis of Fourier Transform Infrared (FTIR)

FTIR spectrophotometer analysis is used to determine which functional groups are contained in a product. The working principle of an FTIR spectrophotometer is to identify the functional groups of a compound based on the infrared absorption of that compound [16].

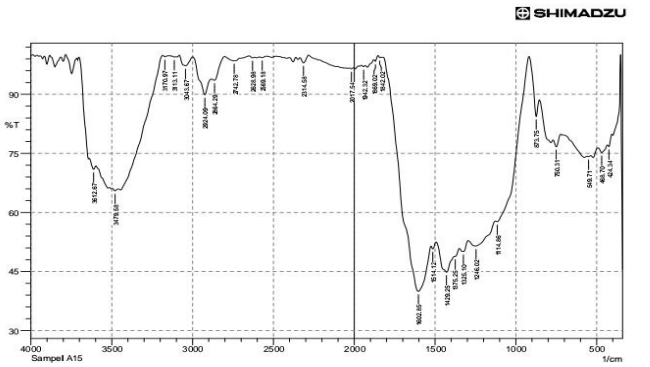

Figure 8. FTIR spectra of walnut shell charcoal briquettes containing an adhesive concentration of 15 grams

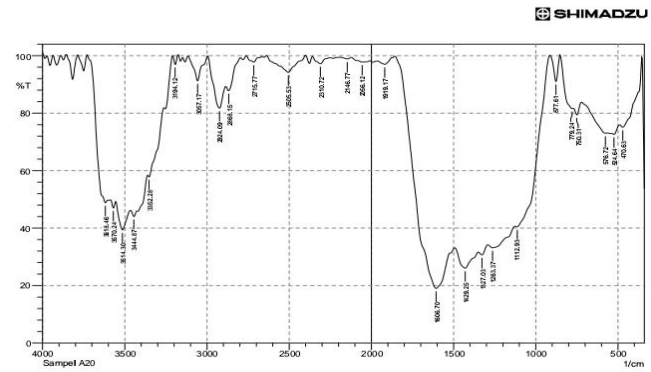

Figure 9. FTIR spectra of walnut shell charcoal briquettes with an adhesive concentration of 20 grams

Table 2. Functional Groups in the FTIR Spectra of Walnut Shell Charcoal Briquettes Adhesive Concentration 15 grams

Wave number value obtained (cm^{-1})	Library (cm^{-1})	Function Group
3442.91 cm^{-1}	3200-3600 cm^{-1}	O-H
2926.01 cm^{-1} 2864.29 cm^{-1}	2850-2970 cm^{-1}	C-H aliphatic
1602.85 cm^{-1}	1600-1820 cm^{-1}	C=C aromatic
1114.86 cm^{-1}	1020-1250 cm^{-1}	C-O
750.31 cm^{-1}	690-900 cm^{-1}	C-H ring aromatic

Table 3. Functional Groups in the FTIR Spectra of Walnut Shell Charcoal Briquettes 20 gram Adhesive Concentration

Wave number value obtained (cm^{-1})	Library (cm^{-1})	Function Group
3444.87 cm^{-1}	3200-3600 cm^{-1}	O-H
2924.09 cm^{-1}	2850-2970 cm^{-1}	C-H aliphatic
1606.70 cm^{-1}	1600-1800 cm^{-1}	C=C aromatic
1429.65 cm^{-1}	1500-1400 cm^{-1}	C-C aliphatic
1112.93cm^{-1}	1300-1050 cm^{-1}	C-O

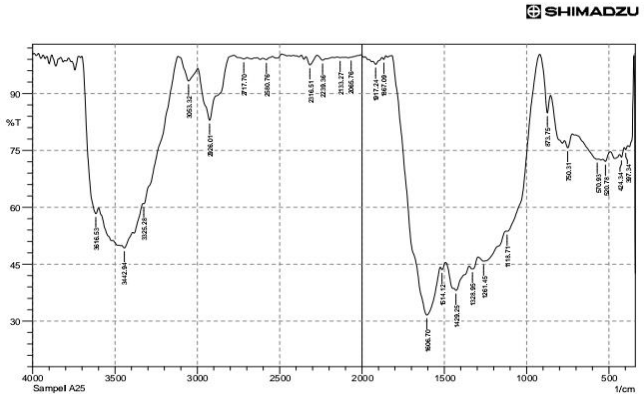

Figure 10. FTIR spectra of walnut shell charcoal briquettes with an adhesive concentration of 20 grams

Table 4. Functional groups identified in FTIR spectra of walnut shell charcoal briquettes prepared with 20 g of adhesive

Wave number value obtained (cm^{-1})	Library (cm^{-1})	Function Group
3442.94 cm^{-1}	3200-3600 cm^{-1}	O-H
2924.09 cm^{-1}	2850-2970 cm^{-1}	C-H aliphatic
1606.70 cm^{-1} 1515.12 cm^{-1}	1650-1400 cm^{-1}	C=C aromatic
1461.45 cm^{-1}	1470-1340 cm^{-1}	C-H alkanes
750.31 cm^{-1}	995-675 cm^{-1} 900-690 cm^{-1}	C-H ring aromatic

4. Discussion

4.1 Charcoal Briquette Production

The raw material to be used must have a high chemical content of hemicellulose or cellulose, lignin, and extractive substances. Walnut shells contain 17.74% cellulose, 36.06% hemicellulose, and 36.90% lignin. Given the relatively high lignocellulose content, walnut shells as an organic compound have the potential to serve as an alternative fuel source, such as charcoal briquettes.

This study used red dragon fruit peel, which contains approximately 10.80% pectin, while the pectin content in dried red dragon fruit peel ranges from 14.6% to 20.14%. In this study, dried dragon fruit peel was used as a binder in the production of charcoal briquettes.

The charcoal briquette production process involves several stages: carbonization (charring), mixing, briquette molding, briquette drying, and testing (physical and chemical properties). In the production of coconut shell briquettes, the shells are first dried under sunlight until completely dry to reduce the moisture and oil content of the coconut shells and facilitate the carbonization process. The carbonization process in this study used cans to prevent the combustion products from turning into ash, with a carbonization duration of 3 hours.

Next, the charcoal powder was mixed with dried red dragon fruit peel at concentrations of 15 g, 20 g, and 25 g, and 85 ml of distilled water was added. The purpose of mixing charcoal powder and adhesive is to create a thin layer of adhesive on the surface of the charcoal particles. The use of adhesive aims to strengthen the bonds between particles [14]. The adhesive concentration was varied to determine the optimal adhesive concentration for the resulting charcoal briquettes.

The molding process is carried out after the charcoal briquette mixture is evenly mixed. The briquette mixture is then molded and pressed using a press machine with a pressure of 10 MPa. The higher the pressure applied, the greater the density and strength of the briquette.

The subsequent phase involves sun-drying the charcoal briquettes for a duration of 4 days. The drying process aims to reduce the moisture content from the adhesive solvent, aquadest, to facilitate the combustion of the briquettes.

The dried charcoal briquettes are subsequently tested to ascertain their properties in compliance with Indonesian National Standards (SNI). including density, compressive strength, moisture content, ash content, calorific value, volatile matter content, and fixed carbon content.

4.2. Testing the Characteristics of Charcoal Briquettes

4.2.1 Density

The results of the density study (Figure 1) show that the highest density value was found at a concentration of 25 grams, which was 0.8508 g/cm³, and the lowest at a concentration of 15 grams, which was 0.7805 g/cm³. Based on the research data, density is directly proportional to the concentration of the adhesive used. The higher the adhesive concentration, the higher the density value. This is because the pectin in the dragon fruit adhesive forms hydrogen bonds with cellulose (Figure 11), where a higher adhesive concentration results in more adhesive filling the pores of the charcoal briquettes, thereby improving the bond between the adhesive and the charcoal powder because the charcoal particles can bind more tightly together and become denser [17].

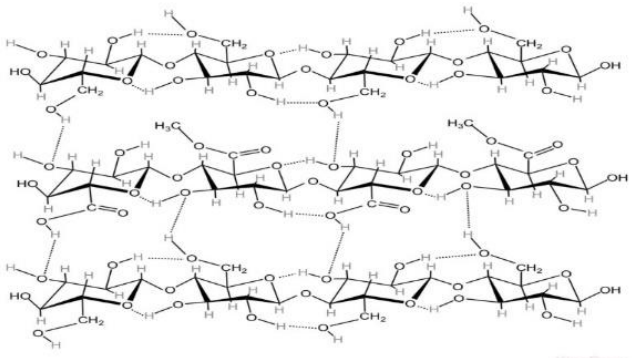

Figure 11. Intra and Inter-Cellulose and Pectin Hydrogen Bonds

4.2.2. Strong Pressure

The results of the study based on Figure 3 show that the highest compressive strength value at a concentration of 15 grams is 14.9884 kg/cm², followed by a concentration of 20 grams at 12.3119 kg/cm², and a concentration of 25 grams has the lowest compressive strength at 5.8890. The compressive strength of charcoal briquettes is affected by the density and physical structure of the briquettes. Briquettes with high density and a more compact structure will have higher compressive strength.

4.2.3 Calorific Value

The most important parameter in fuel production is calorific value. A higher value indicates that the generated charcoal briquettes exhibit superior quality. The moisture, vapor, ash, and carbon content of briquettes affect how high or low their calorific value is [18]. The calorific value is used for efficiency (savings), meaning that if the calorific value per unit is low, then the amount of raw material used for combustion or heating will be less [19].

A higher calorific value indicates superior briquette quality. An increase in calorific value can be influenced by variations in the concentration of the adhesive used. As the starch content increases, the calorific value obtained decreases. The calorific value is additionally affected by the drying process. The longer the drying time of the briquettes, the higher the calorific value due to the decrease in moisture content.

The calorific value results of this study did not meet the SNI standard (01-6235-2000), which requires a minimum calorific value of 5000 cal/g, and did not meet the charcoal briquette standard. However, among all the calorific value tests, the highest value was obtained at a binder concentration of 15 grams, with a calorific value of 4716.28 kcal/g. This calorific value already meets the Indonesian National Standard (SNI) 8021: 2014, which requires a minimum calorific value of 4000 kcal/g, due to the appropriate mixture ratio between charcoal powder and red dragon fruit peel adhesive. The analysis of variance results indicate that the type of adhesive, powder size, and their interaction significantly influence the calorific value [20].

4.2.4 Water Content

The moisture content in charcoal briquette production greatly affects the calorific value and ignition process of a briquette fuel. Moisture content testing is conducted to determine the water content in briquettes with different adhesive concentrations. Briquettes with minimal moisture content yield elevated calorific values and combustion rates, and conversely.

Figure 4 illustrates the moisture content value of the 15-gram adhesive concentration increases to the 20-gram adhesive concentration and continues to increase to the 25-gram adhesive concentration. This is consistent with the research conducted by [21], which indicates that the water content is directly proportional to the adhesive concentration used, as each adhesive concentration has a different amount. The moisture content test results for each adhesive concentration did not exceed 8%, with a moisture content range of 5.9777%–7.3874%, meeting the SNI 01-6235-2000 standard of <8%.

4.2.5 Ash Content

Ash content is the carbon residue from the combustion process. The ash content in adhesives or raw materials affects the ash content, with silica as the main component of ash that has the most significant effect on the calorific value of charcoal briquettes produced [14]. Figure 5, it was found that the ash content of walnut shell charcoal briquettes rose with higher adhesive concentrations. This indicates that the higher the ash content in the briquettes, the lower the calorific value produced. Conversely, the lower the ash content in the briquettes, the higher the calorific value produced [22]. The research results show that only the 15-gram adhesive concentration meets the SNI (01-6235-2000) standard with an ash content of <8%, while the 20-gram and 25-gram adhesive concentrations do not meet the charcoal briquette standards of all countries, including Indonesia, with an ash content of 8%.

4.2.6 Volatile Substance Content

Volatile matter content is the part of the briquette that will turn into product when heated without air at a temperature of ± 9500°C. Volatile matter content includes combustible gases such as hydrogen, carbon monoxide (CO), and methane (CH_4), along with non-combustible gases such as CO_2 and H_2O. The volatile matter content affects the completeness of combustion and the intensity of the flame. The higher the volatile matter content, the faster the fuel will burn and the more smoke it will produce when the charcoal briquette is ignited [23] as shown in Figure 6.

The high or low levels of volatile substances are influenced by the substances extracted from the raw charcoal material and other charcoal chemicals. Additionally, another cause is the inefficient carbonation process. As we know, the purpose of carbonation is to break down hydrocarbon compounds such as cellulose and hemicellulose into pure carbon. This is due to the high oxygen content during the carbonation process, which affects how hydrocarbons are broken down. Overall, in this study, the testing of volatile substance levels from the three adhesive concentrations met SNI 01-6235-2000 standards, which is below 15%.

4.2.7 Bound Carbon Content

The fixed carbon content is the proportion of carbon (C) bound in briquettes other than water content, ash, and volatile matter. The fixed carbon content can affect the quality of briquette fuel. A greater fixed carbon concentration correlates with superior briquette quality, and the higher the fixed carbon content, the greater the heat value produced [24]. Testing the fixed carbon content in briquettes aims to determine the carbon content after the carbonization process. Fixed carbon is a substance that provides heat to the briquette, and a higher content indicates a better briquette [25].

The testing of carbon contained in charcoal briquettes is affected by the ash content and volatile matter content. The carbon content will be higher if the water content, ash content, and volatile compounds of the charcoal briquettes are low.

The highest bound carbon content was obtained from a binder concentration of 15 grams at 81.47%, while the lowest bound carbon content was found at a binder concentration of 20 grams at 79.18%. As shown in Figure 7 above, charcoal briquettes made from walnut shells at a binder concentration of 20 grams experienced a decrease followed by an increase at a concentration of 25 grams. This was due to the conventional carbonization process, which resulted in temperatures that did not reach the ideal level, causing the bound carbon content to increase again at a binder concentration of 25 grams.

4.2.8 Analysis of Fourier Transform Infrared (FTIR)

Based on the spectrum in Figure 9, there are several peaks that show absorption at wavelengths. There is an absorption peak with a widened shape at wave number 3442.91 cm^{-1} because it is in the 3600-3200 cm^{-1} region indicating the existence of stretching vibrations of hydroxyl groups (O-H) from hemicellulose and cellulose content in biomass [26]. The wave number with an absorption band peak of 2926.01 cm^{-1} shows an aliphatic C-H functional group indicating hydrocarbon compounds. A long peak occurs at a wave number of 1602.85 cm^{-1} which indicates the vibration of the aromatic C = C functional group [27]. Waves around 1114.86 cm^{-1} indicate the existence of C-O functional groups of carbonyl ester compounds and acetyl bonds. Where when the briquette is heated, the spectra peak changes from steep to sloping in the charcoal briquette wave band. The change is due to the breaking of acetyl bonds that represent hemicellulose bonds due to heating [27]. The wavelength of 750.31 cm^{-1} shows the vibration of the C-H group of aromatic rings or phenolic structures, which are commonly found in lignin, tannin, or other phenolic components present in walnut shells. The main cellulose-building groups consist of O-H, C-H and C-O functional groups. Overall, it can be seen in Table 2.

Based on the FTIR spectra in Figure 9, charcoal briquettes with a concentration of 20 grams appear a peak at 3444.87 cm^{-1}, indicating the existance of hydroxyl (O-H) functional groups that may come from compounds such as cellulose, hemicellulose, or lignin, which are the main components in walnut shells and red dragon fruit peels. The wave peak of 1606.70 cm^{-1} indicates the presence of aromatic C=C groups because it is in the range of 1600-1800 cm^{-1} which indicates the characteristics of the carbon charcoal structure [28].

Changes in the C = C functional group are due to heat treatment (carbonization) which increases lignin acid content, a compound that resembles a lignin component. The wavelength of 1429.65 cm^{-1} with a range of 1500-1400 cm^{-1} indicates the presence of C-C aliphatic amine groups which may indicate the presence of lignin or polysaccharide compounds. The wavelength of 1112.93 cm^{-1} indicates the existance of a C-O functional group because it is in the 1300-1050 cm^{-1} range. This spectrum indicates the presence of organic compounds with -OH, $-CH_2$, and ester or alcohol groups is observable in Table 3.

The outcomes of the FTIR test in Figure 10 show that changes in compound content will decrease after carbonization into a charcoal sample (not skin anymore), which consists of some cellulose and lignin will be decomposed into tar (combustion products), carbon content will increase to 98%, and the rest is ash. The peak wave 3442.94 cm^{-1} because it is in the range of 3200-3600 cm^{-1} indicates the presence of stretching vibrations of O-H hydroxyl functional groups which often come from cellulose, hemicellulose, lignin or pectin which are the main components in walnut shells. Wavelength 2924.09 cm^{-1} the existence of aliphatic C-H groups which may come from lignocellulose or lipid structures. The wavelength of 1606.70 cm^{-1} indicates the presence of an aromatic C=C group because it is in the 1600-1400 cm^{-1} region. The wavelength of 1461.45 cm^{-1} indicates the existence of a C-H bending functional group because it is in the 1300-800 cm^{-1} region which is likely to come from methyl ($-CH_3$) or methylene ($-CH_2-$) groups in lignocellulose components.

The wavelength of 750.31 cm^{-1} is known to include the C-H functional group. After being matched with the literature, it is included in the alkene C-H functional group because it is in the range of 995-675 cm^{-1} and the aromatic ring C-H functional group with a range of 900-690 cm^{-1}. Therefore, in the results of this spectrum what is detected is the C = C functional group on the alkene ring instead of the aromatic ring, it can be concluded that the possibility of the functional group at 750.31 cm^{-1} including the C-H alkene functional group (Table 4).

5. Conclusion

5.1. Summary of the main findings

This study examined the physicochemical characteristics of charcoal briquettes produced from walnut shells using red dragon fruit peel as a natural adhesive. The briquettes prepared with an adhesive

concentration of 15 g exhibited the most favourable performance, with a density of 0.7808 g/cm³, a moisture content of 5.98%, an ash content of 7.64%, a volatile matter content of 10.89%, and a bound carbon content of 81.09%. These values are within or better than the corresponding Indonesian National Standard (SNI) requirements (density > 0.5–0.6 g/cm³, moisture < 8%, ash < 8%, volatile matter < 15%, bound carbon > 77%). Although the compressive strength (14.99 kg/cm²) and calorific value (4716.28 cal/g) did not fully satisfy the SNI criteria, the overall quality parameters indicate that walnut shell briquettes bound with red dragon fruit peel have promising properties for use as a renewable solid fuel.

5.2. Comparison with previous studies

The findings are broadly consistent with previous work by Asmiani (2020), who reported that walnut shell-based briquettes can achieve competitive calorific values and acceptable volatile matter content relative to conventional coal briquettes. In contrast to earlier studies that relied on starch-based binders such as tapioca or sago flour, the present work demonstrates the feasibility of using an adhesive derived from red dragon fruit peel, an agricultural residue naturally rich in pectin. The slightly lower compressive strength and calorific value observed here, compared with briquettes produced using other binders, are plausibly linked to differences in binder composition, particle interactions, and drying conditions. These discrepancies underscore the importance of optimizing binder formulation and process parameters when transitioning to alternative, waste-derived adhesives.

5.3. Theoretical and practical implications

From a theoretical standpoint, the study contributes empirical evidence on the role of natural pectin-based binders in shaping the physical and chemical properties of biomass briquettes. The results support the view that interactions between lignocellulosic feedstock characteristics, adhesive concentration, and processing conditions jointly determine key quality indicators such as density, ash content, volatile matter, and bound carbon. This evidence can inform further modelling and optimisation of binder–biomass systems in solid biofuel research.

From a practical perspective, the use of walnut shells and red dragon fruit peels illustrates a viable waste-to-energy pathway that valorises locally available agricultural residues. The ability to produce briquettes that largely comply with SNI quality parameters suggests that such materials could be integrated into rural and small-scale energy systems as a substitute for firewood or lower-grade coal. More broadly, the findings align with national and global agendas on renewable energy development and waste reduction by demonstrating how agricultural by-products can be transformed into higher-value, cleaner-burning fuels.

5.4. Limitations and directions for future research

Several limitations should be acknowledged. First, while most quality parameters met SNI requirements, the compressive strength and calorific value remained slightly below the recommended thresholds, indicating that the current binder formulation and processing regime are not yet fully optimised. Second, the study focused on laboratory-scale production and did not systematically evaluate combustion emissions or long-term mechanical stability during storage and handling.

Future research should therefore prioritise optimisation of the binder formulation, for example by combining red dragon fruit peel adhesive with other natural binders (such as starch or molasses) to improve compressive strength and energy density. Systematic variation of carbonization conditions and drying regimes is also warranted to enhance carbonization efficiency and fuel performance. In addition, comprehensive assessments of combustion behaviour including emission profiles and burning duration are needed to characterise the environmental performance and user safety of these briquettes. Finally, techno-economic and scalability analyses, particularly in rural or resource-constrained settings, would help to determine the practical feasibility of deploying walnut shell–based briquettes with red dragon fruit peel adhesive at larger scales.

Declarations

Author Contributions: Conceptualization, SR and F; methodology, SR, IR and F.; formal analysis, SR and PN.; investigation, PN and A.; data curation, SR, IR and PN.; writing—original draft preparation, SR, IR and F.; writing—review and editing, PN and A.
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Use of generative AI

During the preparation of this manuscript, the authors used a generative AI language model (ChatGPT, OpenAI) to assist with language editing and refinement

of selected sections (e.g., improving clarity, grammar, and journal-appropriate style). All content generated with the help of this tool was critically reviewed, verified, and, where necessary, substantially revised by the authors. The authors take full responsibility for the integrity, accuracy, and originality of the manuscript.

References

[1] Supriadi, S. Rahmawati, P. H. Abram, . Afadil, N. G. A. M. Parwati, and . Anggraini, "CHARACTERISTICS OF CHARCOAL BRIQUETTES FROM KEPOK BANANA PEEL WASTE (Musa paradisiaca F.) AS ALTERNATIVE FUEL", *RJC*, vol. 15, no. 1, pp. 108–115, 2022, doi: 10.31788/rjc.2022.1516607.

[2] W. G. Santika, T. Urmee, Y. Simsek, P. A. Bahri, and M. Anisuzzaman, "An assessment of energy policy impacts on achieving Sustainable Development Goal 7 in Indonesia", *Energy for Sustainable Development*, vol. 59, pp. 33–48, Dec. 2020, doi: 10.1016/j.esd.2020.08.011.

[3] Afadil, S. Rahmawati, Magfirah, Arwansyah, and R. M. Putri. PHYSICOCHEMICAL CHARACTERISTICS AND FUEL POTENTIAL OF CHARCOAL BRIQUETTES FROM CANDLENUT AND PEANUT SHELL MIXTURES [J]. RJC, 2025, 18(3):1822–1830. doi: 10.31788/rjc.2025.1839366.

[4] M. B. Maina, F. A. Oluwole, and U. A. Mukhtar, "Energy resource from agriculture: prospects and problems", *ATBU J. Sci. Technol. Educ*, vol. 7, no. 4, pp. 118–128, 2019.

[5] F. Rosillo-Calle, "A review of biomass energy – shortcomings and concerns", *J of Chemical Tech & Biotech*, vol. 91, no. 7, pp. 1933–1945, Mar. 2016, doi: 10.1002/jctb.4918.

[6] B. L. Chua, S. F. Tang, A. Ali, and Y. H. Chow, "Optimisation of pectin production from dragon fruit peels waste: drying, extraction and characterisation studies", *SN Appl. Sci.*, vol. 2, no. 4, p. 621, Mar. 2020, doi: 10.1007/s42452-020-2415-y.

[7] A. Singh et al., "Development Changes in the Physicochemical Composition and Mineral Profile of Red-Fleshed Dragon Fruit Grown under Semi-Arid Conditions", *Agronomy*, vol. 12, no. 2, p. 355, Jan. 2022, doi: 10.3390/agronomy12020355.

[8] R. Ciriminna, A. Fidalgo, A. Scurria, L. M. Ilharco, and M. Pagliaro, "Pectin: New science and forthcoming applications of the most valued hydrocolloid", *Food. Hydrocoll.*, vol. 127, p. 107483, Jun. 2022, doi: 10.1016/j.foodhyd.2022.107483.

[9] D. R. Bagal-Kestwal, M. H. Pan, and B. Chiang, "Properties and Applications of Gelatin, Pectin, and Carrageenan Gels", pp. 117–140, Aug. 2019, doi: 10.1002/9781119301714.ch6.

[10] P. Nanou, W. J. J. Huijgen, M. C. Carbo, and J. H. A. Kiel, "The role of lignin in the densification of torrefied wood in relation to the final product properties", *Biomass and Bioenergy*, vol. 111, pp. 248–262, Apr. 2018, doi: 10.1016/j.biombioe.2017.05.005.

[11] Z. Zhu et al., "High-strength, lightweight and sustainable lignin contained cellulose nanofiber bulk materials for plastic replacement", *Ind. Crops. Prod.*, vol. 185, p. 115106, Oct. 2022, doi: 10.1016/j.indcrop.2022.115106.

[12] N. Asmiani, A. Nawir, N. Jafar, A. J. Rinaldi, and S. Widodo, "Beneficiation of canary shell as a mixture of coal briquette", *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 473, no. 1, p. 012107, Mar. 2020, doi: 10.1088/1755-1315/473/1/012107.

[13] S. Rahmawati, . Pathuddin, J. Sakung, . Suherman, A. Fudholi, and L. Sushmita, "The utilization of corncob for the manufacture of charcoal briquette as an alternative fuel", *J. Phys.: Conf. Ser.*, vol. 1563, no. 1, p. 012022, Jun. 2020, doi: 10.1088/1742-6596/1563/1/012022.

[14] P. Ningsih et al., "CHEMICAL AND PHYSICAL ATTRIBUTES OF CHARCOAL BRIQUETTES MADE FROM A MIXTURE OF KETAPANG FRUIT SHELL (Terminalia Catappa L) AND CORN COB (Zea Mays)", *RJC*, vol. 17, no. 4, pp. 1773–1783, 2024, doi: 10.31788/rjc.2024.1618931.

[15] Sitti Rahmawati et al., "THE UTILIZATION OF DURIAN PEELS (Durio zibethinus) FOR THE MANUFACTURING OF CHARCOAL BRIQUETTES AS ALTERNATIVE FUEL", *J. Pengelolaan Sumberd. Alam dan Lingkung. (Journal Nat. Resour. Environ. Manag*, vol. 13, no. 1, pp. 76–87, 2023, doi: 10.29244/jpsl.13.1.76-87.

[16] I. Siddique, "Exploring Functional Groups and Molecular Structures: A Comprehensive Analysis using FTIR Spectroscopy", *SSRN Journal*, vol. 9, no. 2, pp. 70–76, 2024, doi: 10.2139/ssrn.4886526.

[17] P. Li and R. Liu, "Cellulose Gels and Microgels: Synthesis, Service, and Supramolecular Interactions", *Advances in Polymer Science*, pp. 209–251, 2015, doi: 10.1007/978-3-319-15404-6_6.

[18] F. Inegbedion, "Estimation of the moisture content, volatile matter, ash content, fixed carbon and calorific values of saw dust briquettes", *MANAS J. Eng*, vol. 10, no. 1, pp. 17–20, 2022.

[19] M. Lubwama, V. A. Yiga, and H. N. Lubwama, "Effects and interactions of the agricultural waste residues and binder type on physical properties and calorific values of carbonized briquettes", *Biomass Conv. Bioref.*, vol. 12, no. 11, pp. 4979–4999, 2022, doi: 10.1007/s13399-020-01001-8.

[20] L. M. A. Ramdani, S. Ahzan, and D. S. B. Prasetya, "The Effect of the Type and Composition of the Adhesive on the Physical Properties and the Rate of Combustion Hyacinth Biobriquettes", *Jurnal. Kependidikan. Fisika*, vol. 8, no. 2, p. 85, Dec. 2020, doi: 10.33394/j-lkf.v8i2.2786.

[21] K. Hosaka et al., "Relationship between mechanical properties of one-step self-etch adhesives and water sorption", *Dental Materials*, vol. 26, no. 4, pp. 360–367, Apr. 2010, doi: 10.1016/j.dental.2009.12.007.
[22] F. Inegbedion and E. Ikpoza, "Estimation of the Moisture Content, Volatile Matter, Ash Content, Fixed Carbon and Calorific Values of Rice Husk Briquettes", *Proceedings of the International Conference on Industrial Engineering and Operations Management*, pp. 1–9, Apr. 2022, doi: 10.46254/af03.20220100.
[23] H. Juwono et al., "Alternative Liquid Fuel from Catalytic Cracking of Candlenut Oil Biodiesel (Aleurites Moluccana) and PP/PS Plastic Waste", *Journal of Hunan University Natural Sciences*, vol. 49, no. 1, pp. 66–74, Jan. 2022, doi: 10.55463/issn.1674-2974.49.1.9.
[24] X. Jiang et al., "Relationship between thermal properties and structure, composition of briquette through grey relational analysis", *J. Appl. Geophy.*, vol. 206, p. 104786, Nov. 2022, doi: 10.1016/j.jappgeo.2022.104786.
[25] T. Kebede, D. T. Berhe, and Y. Zergaw, "Combustion Characteristics of Briquette Fuel Produced from Biomass Residues and Binding Materials", *Journal of Energy*, vol. 2022, no. 1, pp. 1–10, Mar. 2022, doi: 10.1155/2022/4222205.
[26] R. Md Salim, J. Asik, and M. S. Sarjadi, "Chemical functional groups of extractives, cellulose and lignin extracted from native Leucaena leucocephala bark", *Wood Sci. Technol*, vol. 55, no. 2, pp. 295–313, 2021, doi: 10.1007/s00226-020-01258-2.
[27] L. Bhatia and D. K. Sahu, "SEM & FTIR Analysis of Rice Husk to Assess the Impact of Physiochemical Pretreatment", *JAERI*, vol. 24, no. 6, pp. 1–13, Oct. 2023, doi: 10.9734/jaeri/2023/v24i6556.
[28] T. L. Ting, R. P. Jaya, N. Abdul Hassan, H. Yaacob, D. Sri Jayanti, and M. A. Mohd Ariffin, "A REVIEW OF CHEMICAL AND PHYSICAL PROPERTIES OF COCONUT SHELL IN ASPHALT MIXTURE", *Jurnal Teknologi*, vol. 78, no. 4, Mar. 2016, doi: 10.11113/jt.v78.8002.

参考文:

[1] S. Supriadi、S. Rahmawati、P. H. Abram、A. Afadil、N. Parwanti 和 A. Anggraini, "香蕉皮废弃物（Musa paradisiaca F.）制成的炭块作为替代燃料的特性", Rasayan J. Chem. 15, 第 108-115 页, 2022 年。http://dx.doi.org/10.31788/RJC.2022.1516607
[2] W. G. Santika、T. Urmee、Y. Simsek、P. A. Bahri 和 M. Anisuzzaman, "评估能源政策对印度尼西亚实现可持续发展目标 7 的影响", Energy Sustain. Dev., 第 15 卷, 第 15 期, 第 167-172 页。 59, 第 33-48 页, 2020 年。https://doi.org/10.1016/j.esd.2020.08.011
[3] A. Afadil、S. Rahmawati、M. Magfirah、A. Arwansyah 和 R. Putri, "石栗和花生壳混合物制成的炭块的物理化学特性和燃料潜力", Rasayan J. Chem., 第 18 卷, 第 3 期, 2025 年。http://doi.org/10.31788/RJC.2025.1839366
[4] M. B. Maina、F. A. Oluwole 和 U. A. Mukhtar, "农业能源：前景与问题", ATBU J. Sci. Technol. Educ., 第 7 卷, 第 4 期, 第 118-128 页, 2019 年。
[5] F. Rosillo-Calle, "生物质能综述——缺点和担忧", J. Chem. Technol. Biotechnol., 第 91 卷, 第 7 期, 第 1933-1945 页, 2016 年。https://doi.org/10.1002/jctb.4918
[6] B. L. Chua、S. F. Tang、A. Ali 和 Y. H. Chow, "火龙果皮废弃物果胶生产的优化：干燥、提取和特性研究", SN Appl. Sci., 第 2 卷, 第 4 期, 第 621 页, 2020 年。https://doi.org/10.1007/s42452-020-2415-y
[7] A. Singh 等人, "半干旱条件下红肉火龙果的理化成分和矿物质分布的发育变化", 农学, 第 12 卷, 第 2 期, 第 1771-1776 页, 2016 年。 355, 2022 年。https://doi.org/10.3390/agronomy12020355
[8] R. Ciriminna、A. Fidalgo、A. Scurria、L. M. Ilharco 和 M. Pagliaro, "果胶：最有价值的水胶体的新科学和未来应用", Food Hydrocoll., 第 127 卷, 第 107-483 页, 2022 年。https://doi.org/10.1016/j.foodhyd.2022.107483Get rights and content
[9] D. R. Bagal-Kestwal、M. H. Pan 和 B. Chiang, "明胶、果胶和卡拉胶的性质和应用", Bio monomers green Polym. Compost. Mater., 第 117–140 页, 2019 年。https://doi.org/10.1002/9781119301714.ch6
[10] P. Nanou、W. J. J. Huijgen、M. C. Carbo 和 J. H. A. Kiel, "木质素在烘焙木材致密化过程中与最终产品特性的关系", 生物质和生物能源, 第 111 卷, 第 248–262 页, 2018 年。https://doi.org/10.1016/j.biombioe.2017.05.005
[11] Z. Zhu 等人, "高强度、轻质和可持续的含木质

素的纤维素纳米纤维块状材料用于替代塑料”，Ind. Crops Prod.，第 185 卷，第 248–262 页，2018 年。115106，2022。https://doi.org/10.1016/j.indcrop.2022.115106

[12] N. Asmiani、A. Nawir、N. Jafar、A. J. Rinaldi 和 S. Widodo，“金丝雀壳作为煤球混合物的选矿”，载于 IOP 会议系列：地球与环境科学，2020 年，第 473 卷，第 1 期，第 12107 页。**DOI** 10.1088/1755-1315/473/1/012107

[13] S. Rahmawati、J. Sakung、A. Fudholi 和 L. Sushmita，“利用玉米芯制造木炭球作为替代燃料”，载于《物理学杂志：会议系列》，2020 年，第 1563 卷，第 1 期，第 12107 页。12022. https://doi.org/10. 1088/1742-6596/1563/1/012022

[14] P. Ningsih、S. Rahmawati、D. S. Ahmar、P. H. Abram、M. F. Azzajjad 和 N. Auliana，“由 Ketapang 果壳 (Terminalia Catappa L.) 和玉米芯 (Zea Mays) 混合物制成的木炭煤块的化学和物理属性。”Rasayan J. Chem.，卷。17、没有。2024 年 4 月。http://doi.org/10.31788/RJC.2024.1748931

[15] S. Rahmawati、T. Santoso、V. D. Sangkota 和 P. H. Abram，“利用榴莲皮 (Durio zibethinus) 制造木炭煤球作为替代燃料”，J. Sumberd。马纳杰门。阿拉姆丹林昆甘。（《自然资源与环境管理》杂志，第 13 卷，第 1 期，第 76-87 页，2023 年。https://doi.org/10.29244/jpsl.13.1.76-87

[16] I. Siddique，“探索功能基团和分子结构：使用 FTIR 光谱进行综合分析”，《化学研究杂志》，第 9 卷，第 2 期，第 70-76 页，2024 年。DOI: https://doi.org/10.5281/zenodo.11281698

[17] P. Li 和 R. Liu，“纤维素凝胶和微凝胶：合成、服务和超分子相互作用”，《超分子聚合物网络凝胶》，第 209-251 页，2015 年。https://doi.org/10.1007/978-3-319-15404-6_6

[18] F. Inegbedion，“估算锯末团块的水分含量、挥发性物质、灰分含量、固定碳和热值”，《MANAS 工程杂志》，第 10 卷，第1，第 17-20 页，2022 年。https://doi.org/10.51354/mjen.940760

[19] M. Lubwama、V. A. Yiga 和 H. N. Lubwama，“农业废弃物残留物和粘合剂类型对碳化团块物理性质和热值的影响及相互作用”，生物质转化与生物精炼，第 12 卷，第 11 期，第 4979-4999 页，2022 年。https://doi.org/10.1007/s13399-020-01001-8

[20] L. M. A. Ramdani、S. Ahzan 和 D. S. B. Prasetya，“粘合剂类型和组成对风信子生物团块物理性质和燃烧速率的影响”，Lensa J. Pependidikan Fis.，第 8 卷，第 2 期，第 85-92 页，2020 年。https://doi.org/10.33394/j-lkf.v8i2.2786

[21] K. Hosaka 等al.，“一步自酸蚀胶粘剂的力学性能与吸水率的关系”，Dent. Mater.，第26卷，第4期，第360-367页，2010年。 DOI: 10.1016/j.dental.2009.12.007

[22] F. Inegbedion 和 E. Ikpoza，“稻壳团块水分、挥发分、灰分、固定碳和热值的估算”，2022年。https://doi.org/10.46254/AF03.20220100

[23] H. Juwono 等，“石栗油生物柴油（Aleurites Moluccana）和 PP/PS 塑料废弃物催化裂解制备替代液体燃料”，湖南大学自然科学学报，第49卷，第1期，2022年。https://doi.org/10.55463/issn.1674-2974.49.1.9

[24] X. Jiang 等，“通过灰色关联分析研究团块的热性能与结构、成分的关系”，J.应用地球物理学，第206卷，第104786页，2022年。https://doi.org/10.1016/j.jappgeo.2022.104786

[25] T. Kebede、D. T. Berhe 和 Y. Zergaw，“生物质残渣和粘合材料生产的团块燃料的燃烧特性”，《能源杂志》，第 2022 卷，第 1 期，第 4222205 页，2022 年。https://doi.org/10.1155/2022/4222205

[26] R. Md Salim、J. Asik 和 M. S. Sarjadi，“从本地银合欢树皮中提取的提取物、纤维素和木质素的化学官能团”，《木材科学与技术》，第 55 卷，第 2 期，第 295-313 页，2021 年。https://doi.org/10.1007/s00226-020-01258-2

[27] L. Bhatia 和 D. K. Sahu，“通过 SEM 和 FTIR 分析稻壳来评估物理化学预处理的影响”，《农业生态研究国际杂志》，第 24 卷，第 1 期，第 4222205 页，2022 年。 6，第 1-13 页，2023 年。DOI: 10.9734/jaeri/2023/v24i6556

[28] T. L. Ting、R. P. Jaya、N. A. Hassan、H. Yaacob

、D. S. Jayanti 和 M. A. M. Ariffin, “沥青混合料中椰壳的化学和物理特性综述”, J. Teknol. (Sciences Eng.), 第 78 卷, 第 4 期, 2016 年。 https://doi.org/10.11113/ jt.v78.8002

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